ARKIV FÖR FYSIK Band 11 nr 44

Communicated 28 November 1956 by GEORGE DE HEVESY and HARALD NORINDER

Conduction of electricity through ice and snow

II. Current through a circuit with ice crystal inserted

By REINHARDS SIKSNA

With 16 figures in the text

1. Introduction

When measuring the electrical resistivity of ice crystals with the method of discharging a condenser through ice [2], variations were observed that could be explained by the assumption that something determining the resistivity might be removed with time from the ice crystal or at least displaced in it by the electrical field applied. A variable current could be expected through the crystal in such a case. An attempt to record this current will be described in this paper.

Some difficulties were always encountered when measuring the electrical properties of ice and snow. Influence of different factors was shown on the values measured and on their variations with time. It was not possible to exclude any of the factors present for obtaining a definite dependence on only one of them. For instance, it was not possible to eleminate the effects caused by the electrical field applied when treating the ice crystal under examination, because the electrical field must be applied in order to obtain a current through the crystal. The current was also depending on the length of the time period during which the potential was applied. And, as will be shown below, the treatment of ice by electrical field is one with great influence on the general electric behaviour of the crystals under consideration. It was attempted to avoid these difficulties by variation of the experimental conditions. In view of the limits of the existing possibilities, the influence of the following factors was investigated:

(1) Properties of the electrode surface;
(2) the potential applied;
(3) the time interval during which the potential was applied;
(4) the temperature;
(5) the direction of the current with respect to the optical axis of the crystal.

In addition, the influence of a lasting treatment of the sample was investigated when it was under tension or short-circuited.

Concerning the influence of the properties of the electrode surfaces it has been found by Auty and Cole [1], when measuring dielectric properties of ice, that there is no difference when using heavily gold-plated or well-cleaned and soaked brass electrodes.

2. Experimental arrangement

2.1. *Recording of the current.*—The ice crystal was inserted in a circuit to a battery the polarity of which could be turned (Fig. 1). The current through the crystal was measured by the dropping of the potential across a resistor inserted in the circuit. An amplifier valve was connected with the resistor and the potential difference along the anode resistor of the amplifier was recorded on the moving film of a cathode-ray oscillograph. Time marks for each second were also recorded on the film. The recording device was calibrated with different grid potentials adjusted.

2.2 *Ice crystals.*—All the measurements described were carried out with two pieces of ice cut from one large single crystal of ice prepared and tested with respect to the homogeneity as described in [2]. The dimensions of the ice pieces used were as follows: at the beginning with the electrode surface $S = 2 \times 1.4$ cm^2 and the height $h = 1.2$ cm; for the series with oxidized brass electrodes with $S = 2 \times 1.1$ cm^2 and $h = 1.1$ cm, and for the series with chrome-plated electrodes with $S = 2 \times 1$ cm^2 and $h = 1.1$ cm.

2.3. *Stage for the ice crystals.*—For elimination of a possible difference of the temperature in different heights in the cold-box where the crystals were placed for measuring, a stage as shown in Fig. 2 was constructed. The ice crystals with cylindrical electrodes frozen to their end surfaces were placed on the stage with the axis horizontally. Two different kinds of electrodes were used: (1) chrome-plated and (2) brass covered with an oxide layer. The brass electrodes were oxidized to enhance the uncleanness of the surfaces.

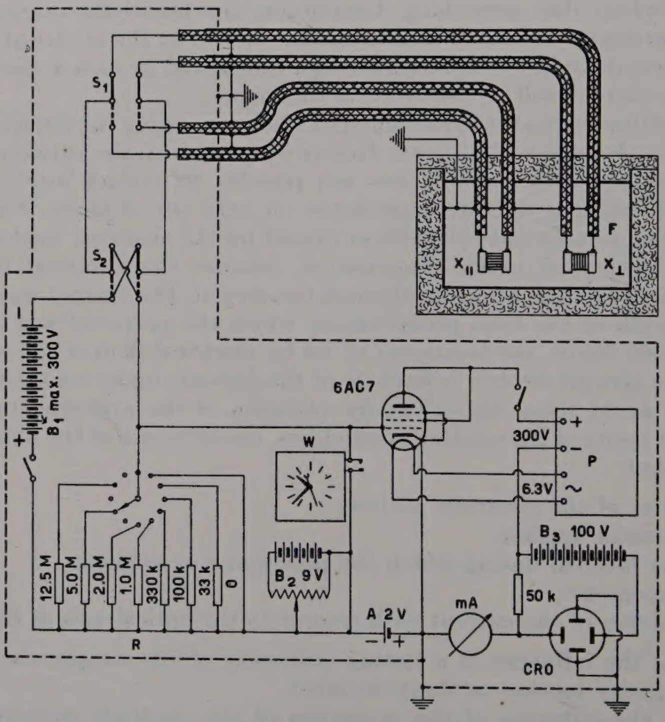

Fig. 1. Schematic diagram of the measuring and recording system. *F*, cold box; $x_{\perp}$ and $x_{\parallel}$, ice crystals; S_1, switch to crystals; S_2, switch for alternation of the current direction; B_1, current battery; *R*, current resistors; *6AC7*, amplifier tube; *W*, clockwork; B_2, battery for calibration of the amplifier; *P*, power supply of the amplifier; *CRO*, cathode-ray oscillograph.

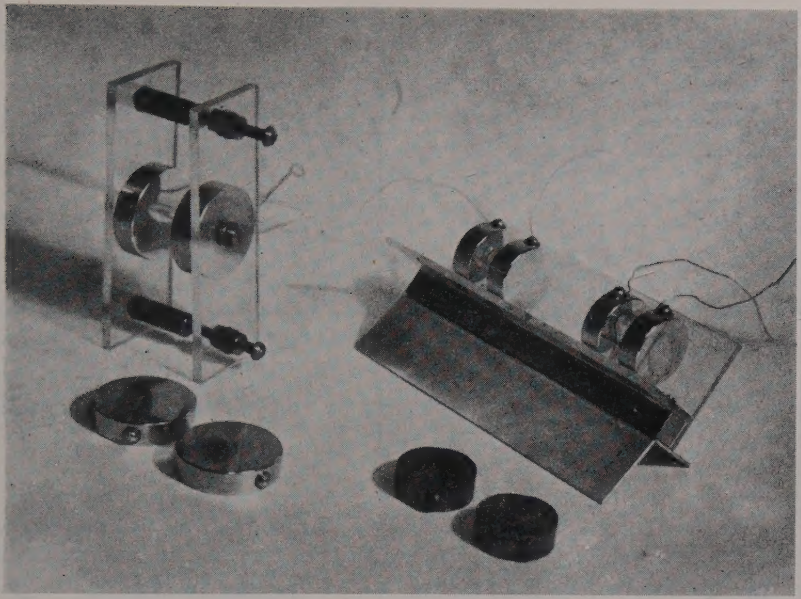

Fig. 2. Stages of the ice crystals; ice crystals; electrodes.

3. Influence of different factors on the current through ice

A general picture of different factors influencing the current through ice crystals is given in Figs. 3 and 4. Series of measurements presented in Fig. 3 were carried out by using the following arrangement. Two similar pieces of ice were cut from the same single ice crystal and the oxidized brass electrodes were frozen to one of the pieces, and the chrome-plated electrodes to the other. The electrodes were so arranged in relation to the crystals that the current passed in parallel to the optical axis. The current through the crystals was recorded by applying rectangular pulses of potential (192 volts) during one minute, and afterwards the polarity of the potential applied was changed. To facilitate a comparison with other measurements the current recorded is not shown in Fig. 3, but this figure shows the conductivity computed

$$\varkappa = \frac{i}{U} \cdot \frac{h}{q},$$

where i is the current recorded, U the potential applied, q the cross section of the crystal, and h its height. The presented time curves of the conductivity, or of the current respectively, show the following effects:

(1) Concerning the electrode properties, one family of curves is shown for the oxidized brass electrodes and another for the chrome-plated electrodes.

(2) During the period (1 min.) of applying a constant potential of 192 volts to the crystal, the current is not constant; it varies with time, for oxidized brass more than for chrome-plated electrodes.

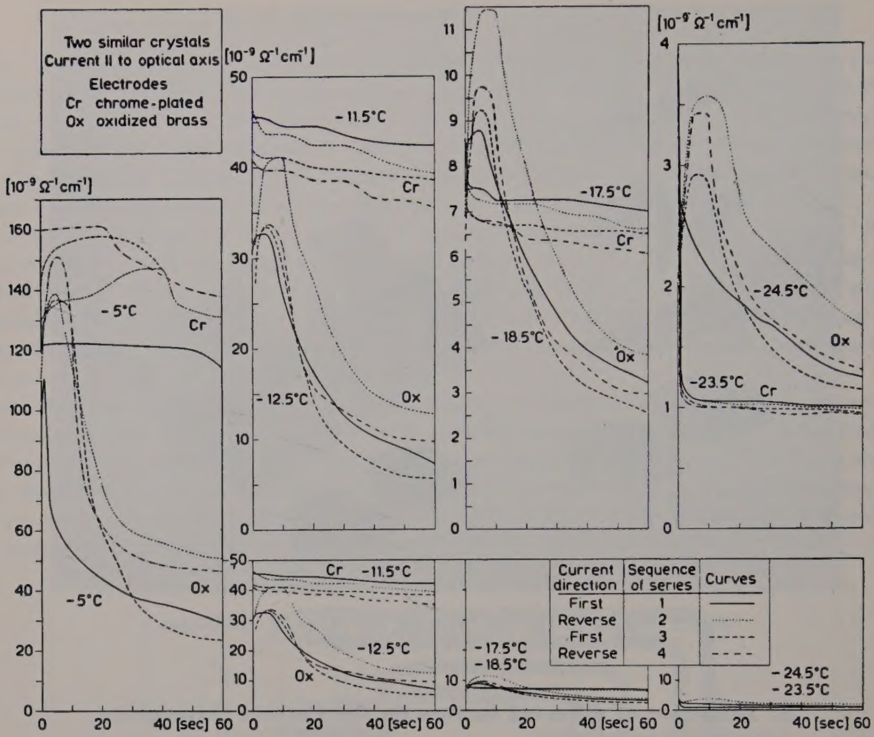

Fig. 3. Conductivity of two similar ice crystals with the current || to the optical axis at decreasing temperatures. *Cr*, chrome-plated electrodes; *Ox*, oxidized brass electrodes.

(3) The current curves are of different shapes when changing the direction of the current.

(4) The current depends considerably on the temperature, but the shapes of the current–time curves are similar.

The series of measurements shown in Fig. 4 were carried out at a constant temperature between −9 and −10°C by using three different potentials of 95, 192 and 300 volts. Pulses of 0.5, 1, 2 and 4 minutes' duration were used and after each of them the direction of the current was changed. The curves obtained are in general of a shape similar to that shown in Fig. 3. By increasing the potenital applied the conductivity decreased considerably with time.

4. Measuring series by using oxidized brass electrodes

For the next series oxidized brass electrodes were frozen to both the crystals used, to the first for the current in parallel to the optical axis, to the second perpendicularly to it. Three recording series (each of 23 minutes' duration) were carried out at a temperature varying between −10° and −11°C and by using a potential of 95 volts during the first series, 192 volts during the second and 300 volts during the third. During each of the series, pulses of 0.5, 1, 2 and 4 minutes' duration were

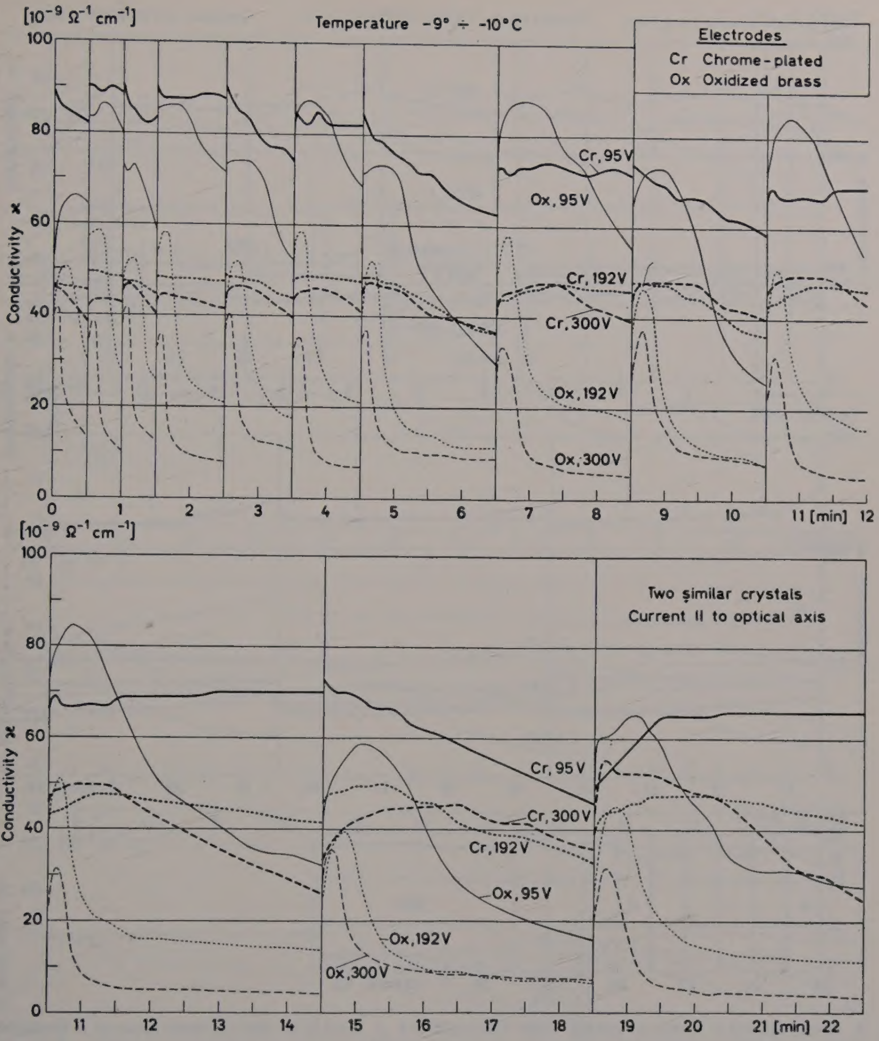

Fig. 4. Conductivity of two similar ice crystals with the current || to the optical axis at a temperature of −9° to −10°C; chrome-plated and oxidized brass electrodes. 0.5, 1, 2 and 4 min. pulses for 95, 192 and 300 V applied to the crystals.

used and after each pulse the direction of the current was changed. The series shown in Fig. 5 were recorded with freshly frozen electrodes. The first notable fact observed was that the current $\perp$ to the optical axis was considerably higher than that || to the optical axis for the potentials applied of 95 and 192 volts. After finishing all the three series (with a duration of 3×23 minutes) a series was repeated at 95 volts. As shown, the conductivity decreased about 5 times, which might be explained on the assumption that carriers were removed by the lasting potential applied. After finishing the recording, the crystals were left without electrical field during 16 hours

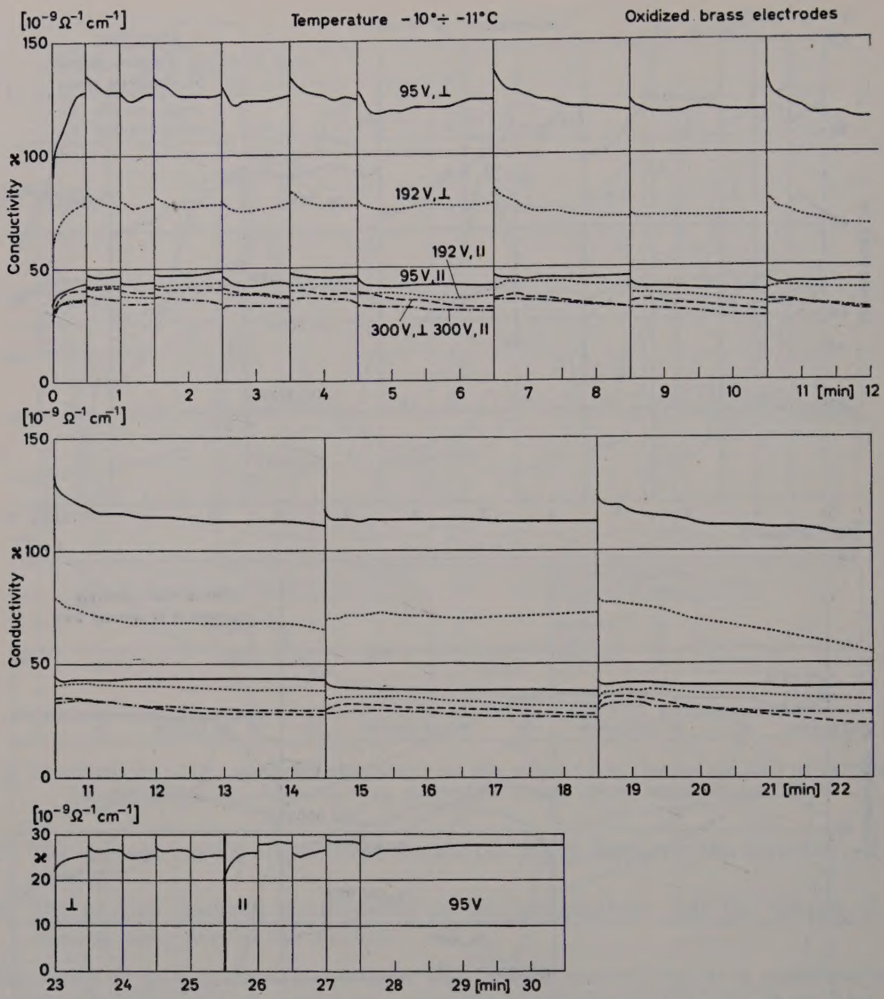

Fig. 5. Conductivity of ice crystals with the current ⊥ and || to the optical axis at a temperature of −10° to −11°C; oxidized brass electrodes. Freshly frozen to the electrodes. 0.5, 1, 2 and 4 min. pulses for 95, 192 and 300 V applied to the crystals.

and a new series was recorded the next day. The results are shown in Fig. 6. The great difference between the current ⊥ and || to the optical axis shown in Fig. 5 at the start of the series cannot be seen in Fig. 6. The conductivity was of the same value as recorded at the end of the previous series, yet the variations during individual pulses were greater. After finishing the recording, a potential of 300 volts was switched to the crystals and they were left during 44 hours with the potential applied. Thereupon, new series were recorded (Fig. 7). A decrease of the conductivity (about 10 times) is noteworthy and a considerable difference between the current ⊥ and || to the optical axis was again observed. During this series the recording was first carried out with 300 volts, then with 192 volts and finally with 95 volts. A series with

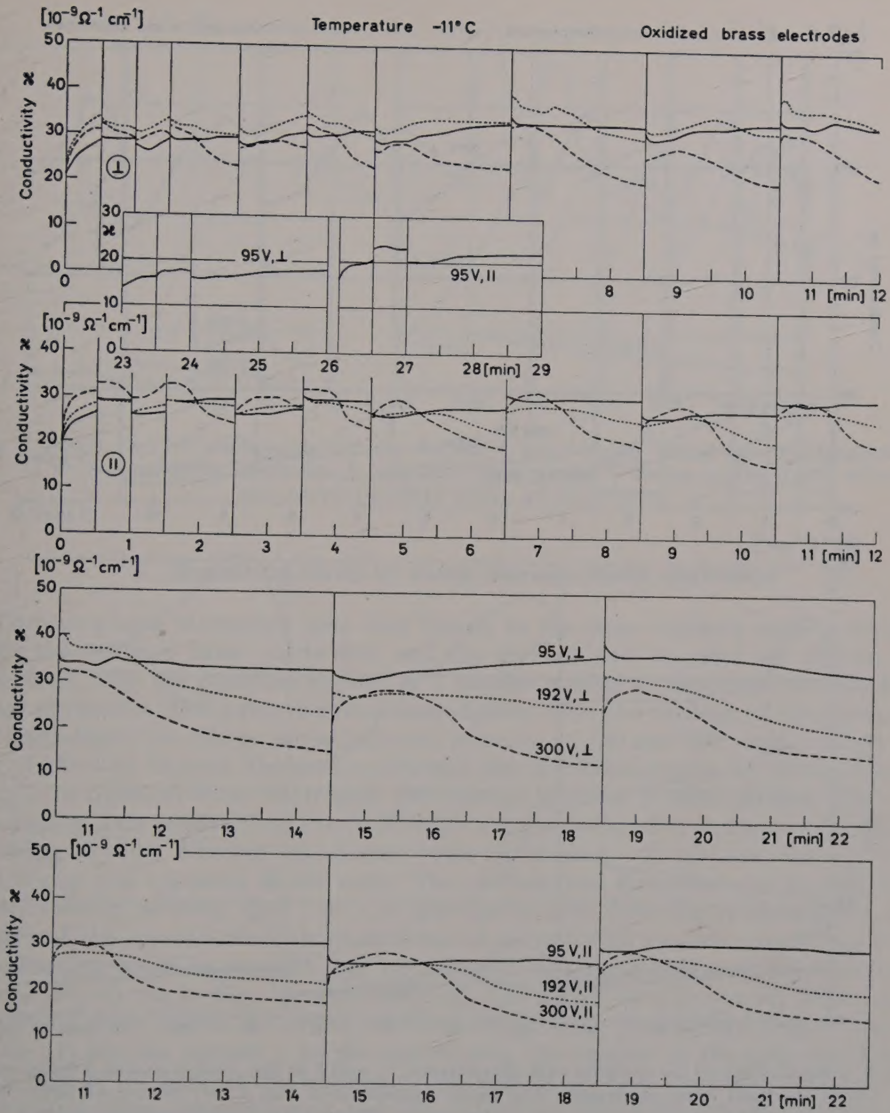

Fig. 6. Conductivity of ice crystals with the current ⊥ and ∥ to the optical axis at a temperature of −11°C; oxidized brass electrodes. The same samples as in Fig. 5, left 16 hours without tension. 0.5, 1, 2 and 4 min. pulses for 95, 192 and 300 V applied to the crystals.

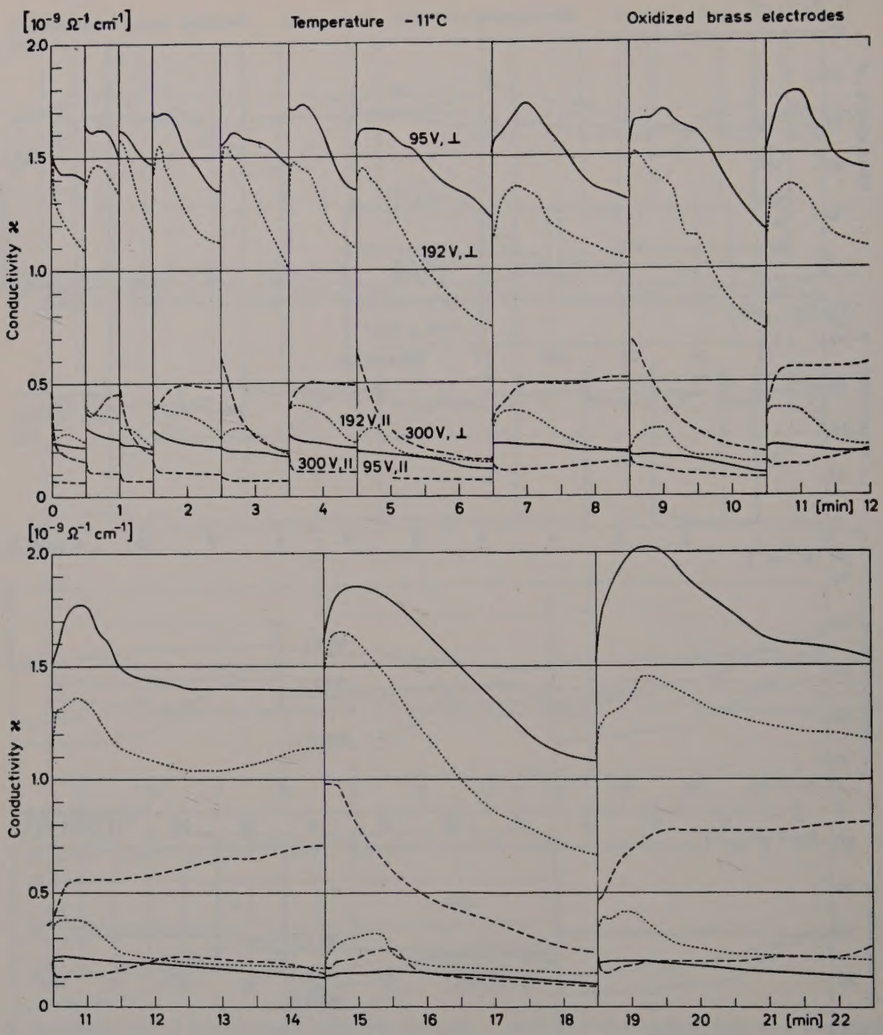

Fig. 7. Conductivity of ice crystals with the current ⊥ and || to the optical axis at a temperature of -11°C; oxidized brass electrodes. The same samples as in Fig. 6, left during 44 hours under tension 300 V. 0.5, 1, 2 and 4 min. pulses for 95, 192 and 300 V applied to the crystals.

300 volts was repeated after finishing the first three series (Fig. 8). An increase of the current can be noted. A preliminary explanation may be as follows: Carriers could be displaced to one or both ends of the crystal when being under tension during a long time and the concentration of the carriers in the middle of the crystal can be low. When changing the polarity several times while recording, some part of the carriers may be displaced from the ends into the crystal and their concentration in the middle of the crystal might be increased.

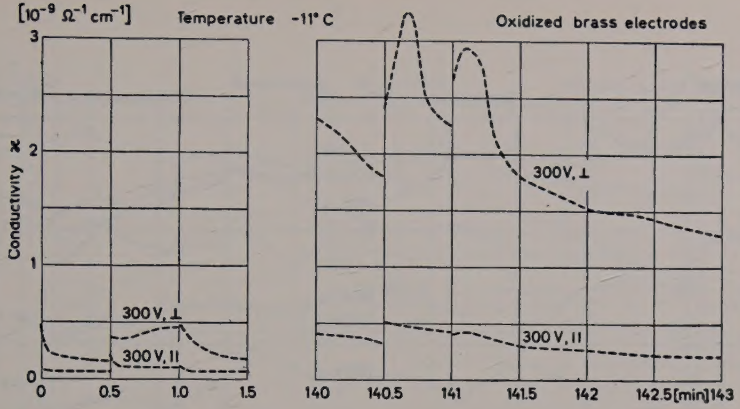

Fig. 8. Conductivity of ice crystals with the current ⊥ and || to the optical axis at a temperature of −11°C; oxidized brass electrodes. Pulses of 0.5 min. at 300 V shown in Fig. 7 and continuation, after complete series, of that figure.

5. Measuring series by using chrome-plated electrodes

Chrome-plated electrodes were now frozen to the same crystals used previously with the oxidized brass electrodes, and the current was recorded by varying the treatment with the potential applied in a manner similar to that used with oxidized brass electrodes. The series recorded immediately after the freezing of the electrodes by using first a 90-volt potential followed by series at 180 and 280 volts are shown in Fig. 9. As may be seen, the curves obtained are in general similar to those shown in Fig. 5 for oxidized brass electrodes. The current is about 3 times greater, and ⊥ to the optical axis greater than || to it. Notable are the peaks after starting of the pulses by using 90 volts. When the three main series (duration 3 × 23 minutes) were finished, one series was repeated at 90 volts. The current was decreased and no difference was observed between that || or ⊥ to the optical axis. After the recording, the electrodes of the crystals were short-circuited (it seemed that by such a treatment some equalization could be reached, but no influence was observed), and after 16 hours new series, shown in Fig. 10, were recorded. The levels were in general at the same heights as those at the end of the previous series. Some peculiarities shown must be noted: (1) For the current ⊥ to the optical axis, the current at 180 volts was higher than that at 90 volts at the beginning, but during the first 2 minutes' pulses it was below and during the following time the difference increased; (2) for the current || to the optical axis, the current at 280 volts was higher than the current at 180 and 90 volts during the first pulses, but at the end of the 2 minutes' pulses it was below that of 180 volts and during the middle of the 4 minutes' pulses also below that at 90 volts. After finishing the recording, a potential of 280 volts was switched to the crystals during 16 hours and after that new series, presented in Fig. 11, were recorded. During these series the recording was first carried out with 280 volts, then with 180 volts, and the last series with 90 volts. The comparatively small current at the beginning increased gradually during the recording. It seems that these series are the purest series recorded. An almost continual changing of the values reached can be seen when turning the direction of the current. There is a notable sequence

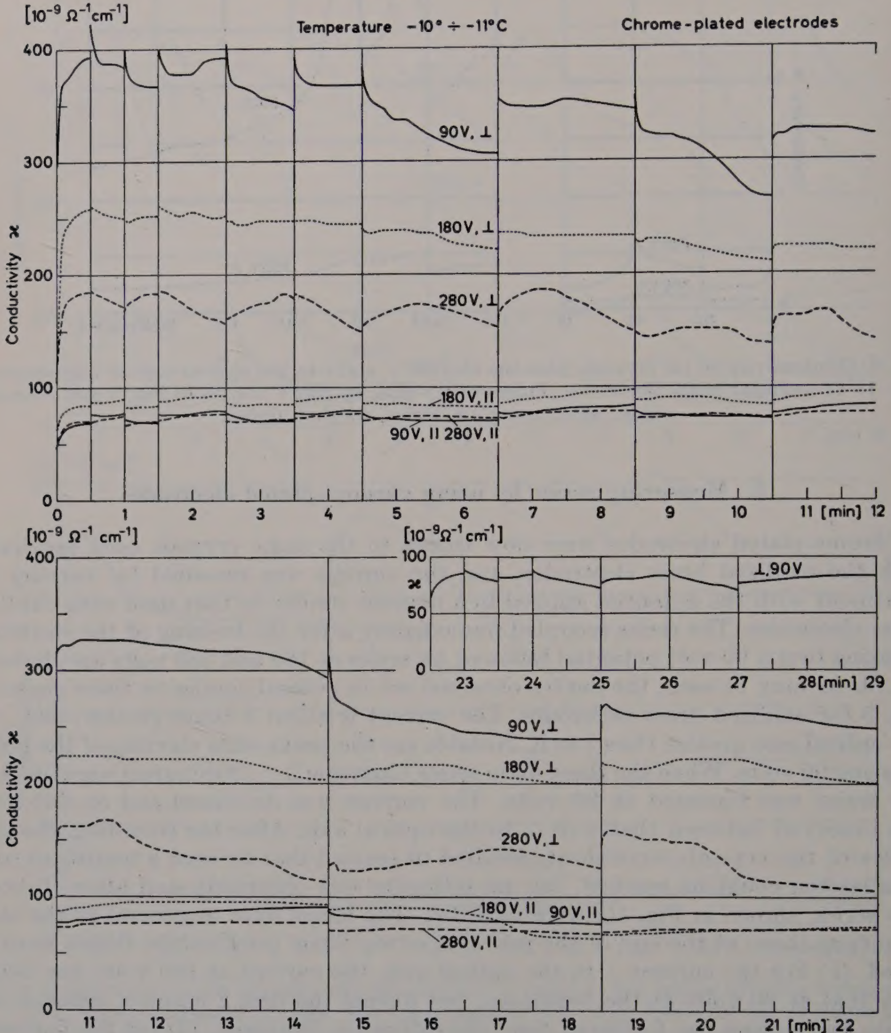

Fig. 9. Conductivity of ice crystals with the current ⊥ and || to the optical axis at a temperature of −10° to −11°C. The same crystals as used with the oxidized brass electrodes freshly frozen to the chrome-plated electrodes. 0.5, 1, 2 and 4 min. pulses of 90, 180 and 280 volts.

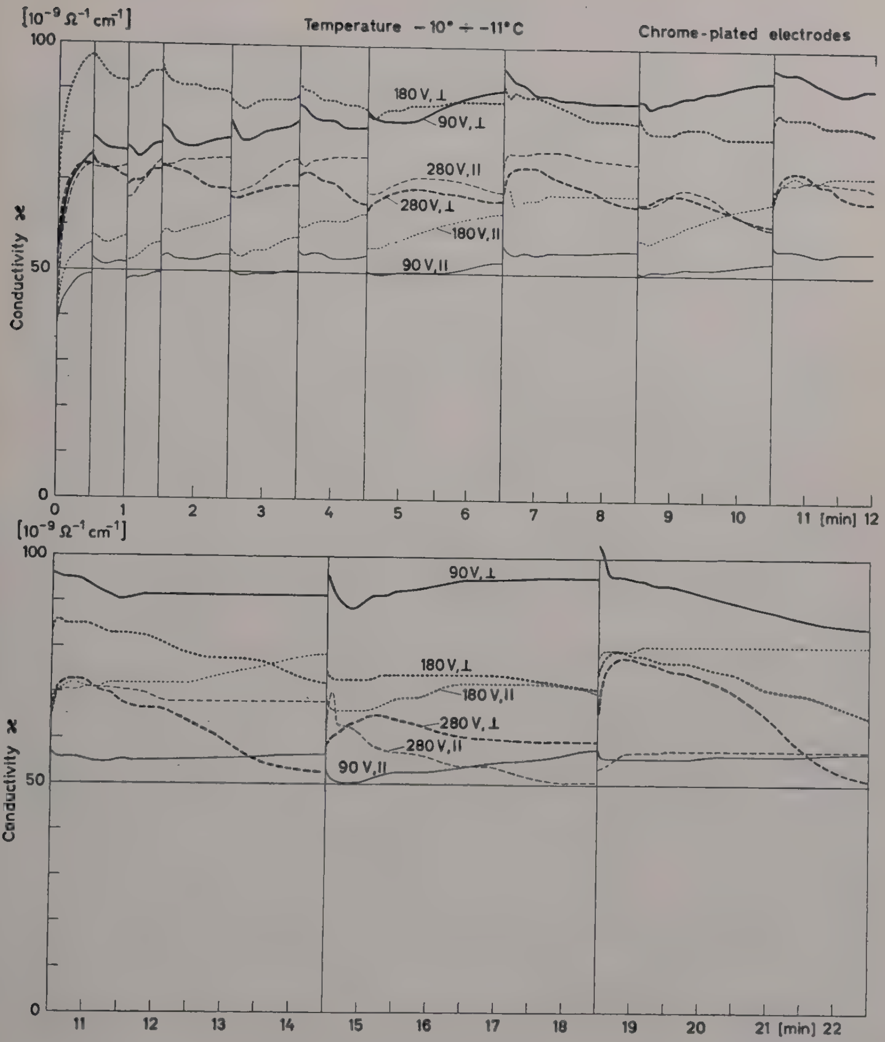

Fig. 10. Conductivity of ice crystals with the current ⊥ and || to the optical axis at a temperature of −10° to −11°C; chrome-plated electrodes. Continuation of series shown in Fig. 9, after crystals being short-circuited during 16 hours. 0.5, 1, 2 and 4 min. pulses of 90, 180 and 280 volts.

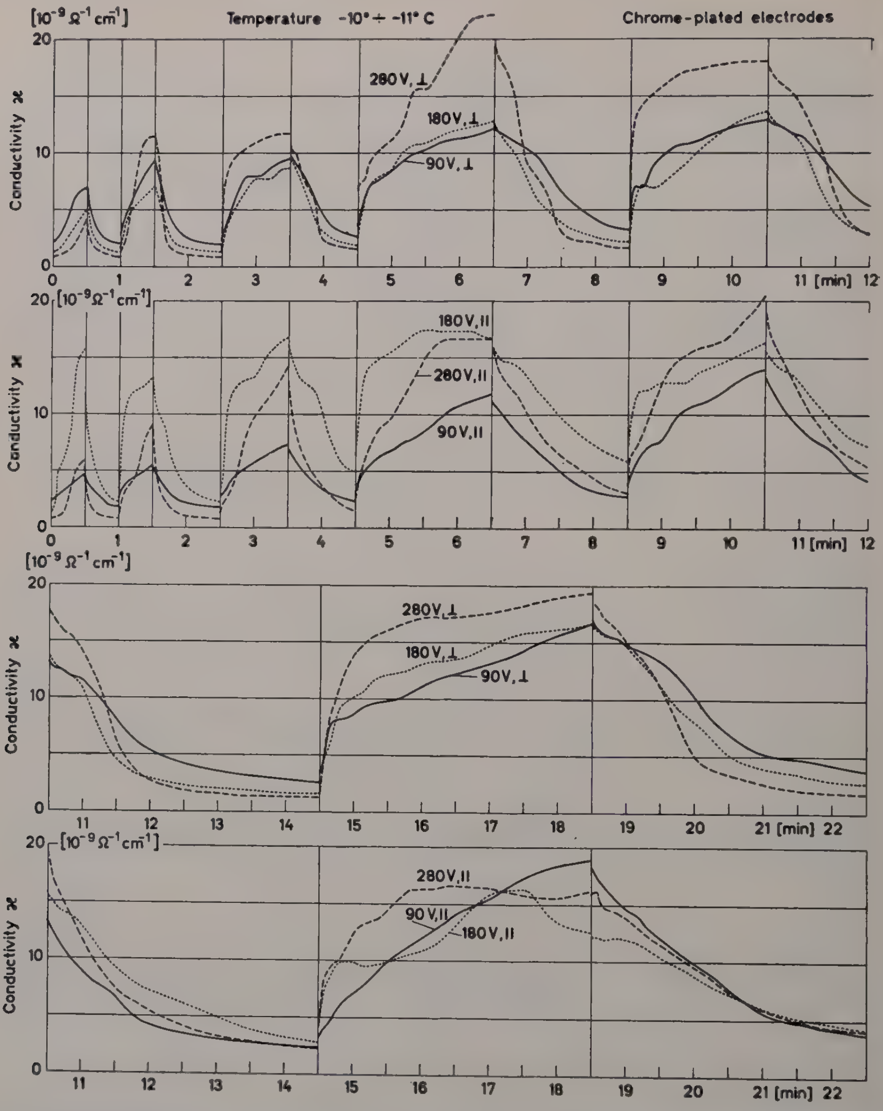

Fig. 11. Conductivity of ice crystals with the current ⊥ and || to the optical axis at a temperature of $-10°$ to $-11°$C; chrome-plated electrodes. Continuation of series shown in Fig. 10, after crystals being connected with a 280 volt battery during 16 hours. 0.5, 1, 2 and 4 min. pulses of 280, 180 and 90 volts.

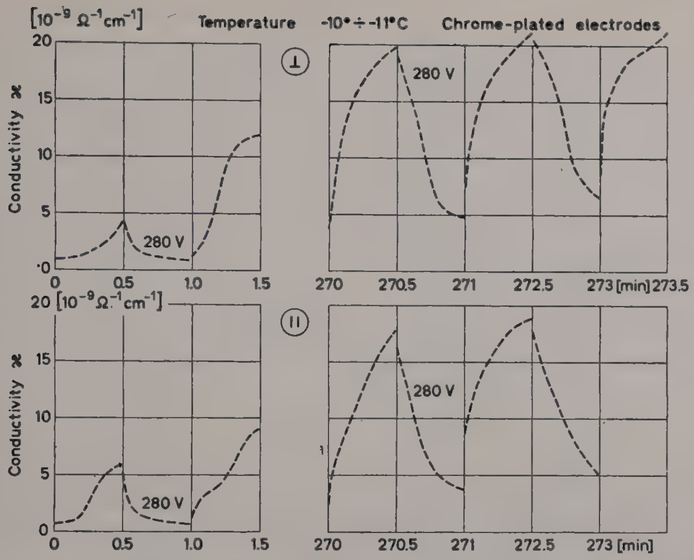

Fig. 12. Conductivity of ice crystals with the current ⊥ and || to the optical axis at a temperature of −10° to −11°C; chrome-plated electrodes. Pulses of 0.5 min. and 280 volts shown in Fig. 11 and continuation after complete series shown in the same figure.

of the curves for different potentials applied when the current increased and decreased, especially for the current ⊥ to the optical axis. This may possibly be explained by considerations similar to those made concerning a similar effect in the case of the oxidized brass electrodes. After finishing the recording presented in Fig. 11, series of 0.5 minute pulses were repeated at 90 volts. This series is shown in Fig. 12 where the 0.5 minute pulses from the starting part of Fig. 11 are also plotted for comparison. As may be seen, the conductivity gradually increased after a lasting treatment when changing the polarity.

6. Dependence of the conductivity on the temperature

In Figs. 13, 14, 15 and 16 the variations of the conductivity of ice are shown in dependence on the temperature by using chrome-plated electrodes. The procedure of the treatment during the recording was as follows: for each temperature three 2 minutes' pulses were used, the first (I) pulse with polarity opposite to that applied earlier when the crystals were connected to the battery during a certain time period (when the crystals had earlier been left without tension this condition was not considered); the second (II) pulse with changed polarity; and the third (III) with the same polarity as during (I). When the series are started after the crystals have been under tension for a time, the curve (I) shows a tendency to increase which can be explained by assuming that a displacement of carriers into the crystal was caused by the reversed potential from the layers near the electrodes where they were removed by the lasting potential applied before. Therefore the current increased. By turning the polarity (curves II) the current decreased, and the carriers could be replaced to

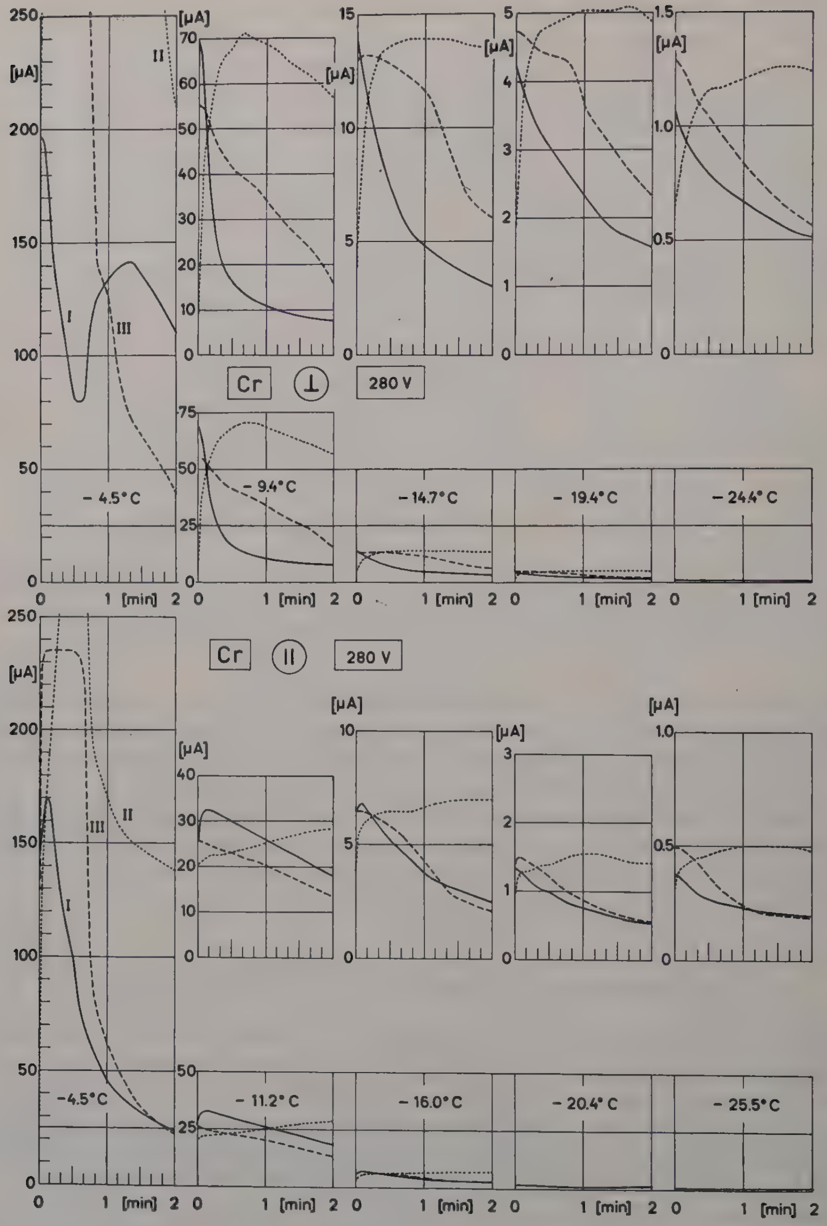

Fig. 13. Current through ice crystals ⊥ and || to the optical axis in dependence on decreasing temperature. Chrome-plated electrodes. Rectangular pulses of 2 minutes and 280 volts. Before the measuring series the crystals have been short-circuited during 16 hours.

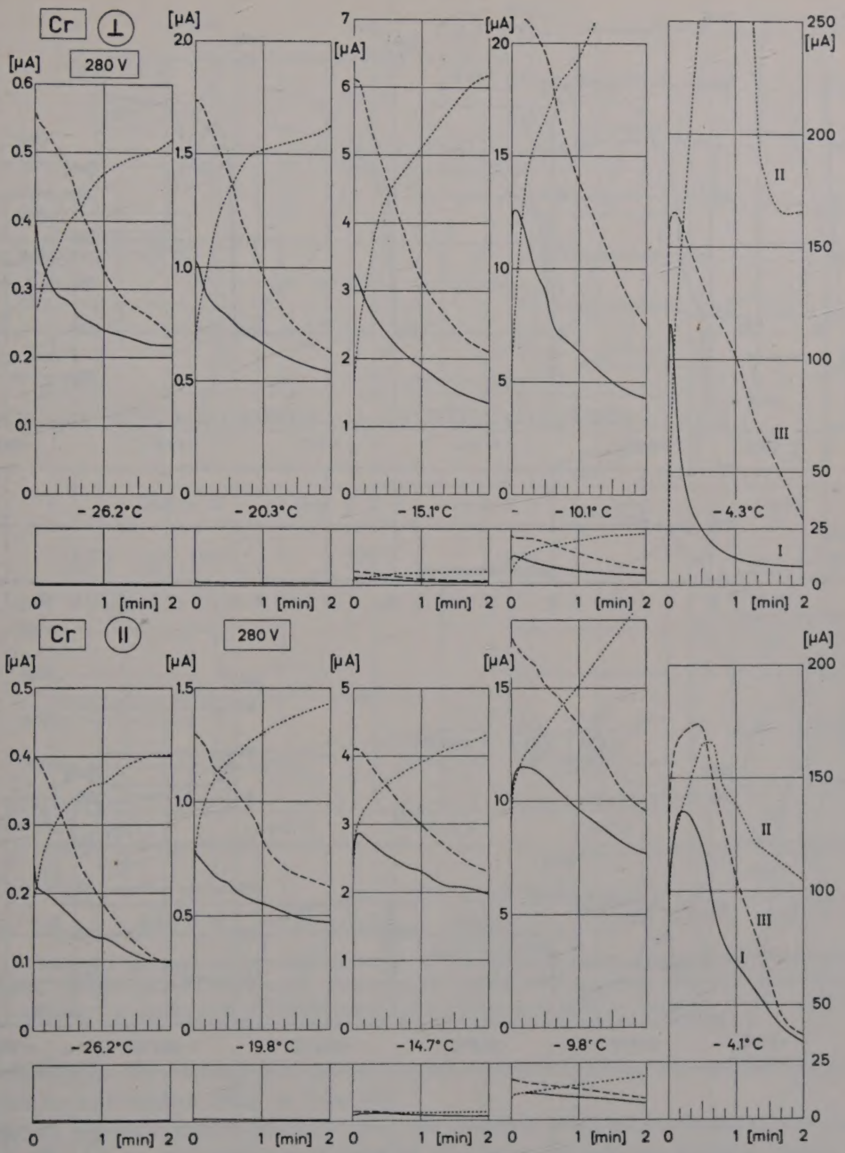

Fig. 14. Current through ice crystals ⊥ and ‖ to the optical axis in dependence on increasing temperature. Chrome-plated electrodes. Rectangular pulses of 2 minutes and 280 volts.

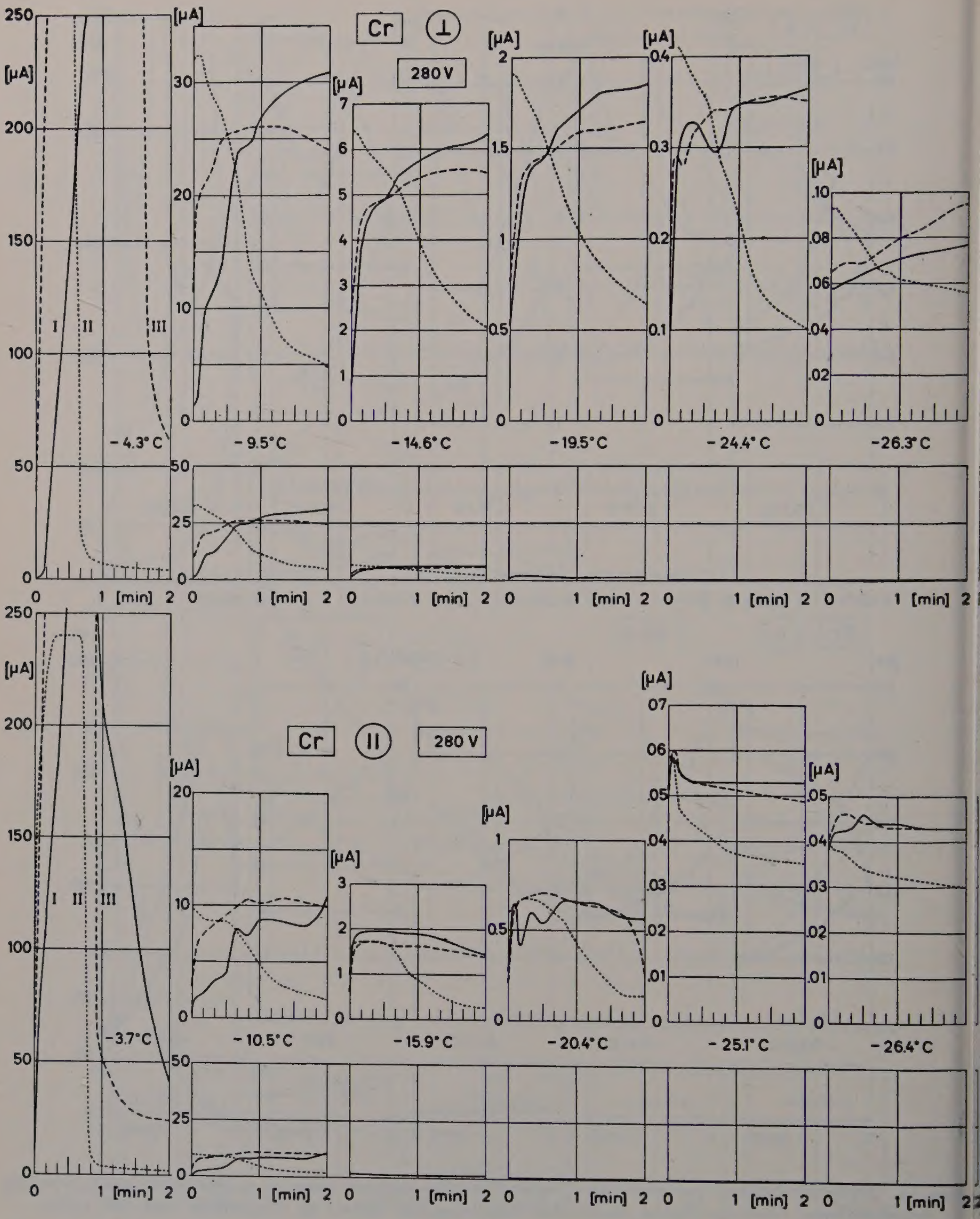

Fig. 15. Current through ice crystals ⊥ and || to the optical axis in dependence on decreasing temperature. Chrome-plated electrodes. Rectangular pulses of 2 minutes and 280 volts. Before the measuring series the crystals have been connected with a battery of 280 volts.

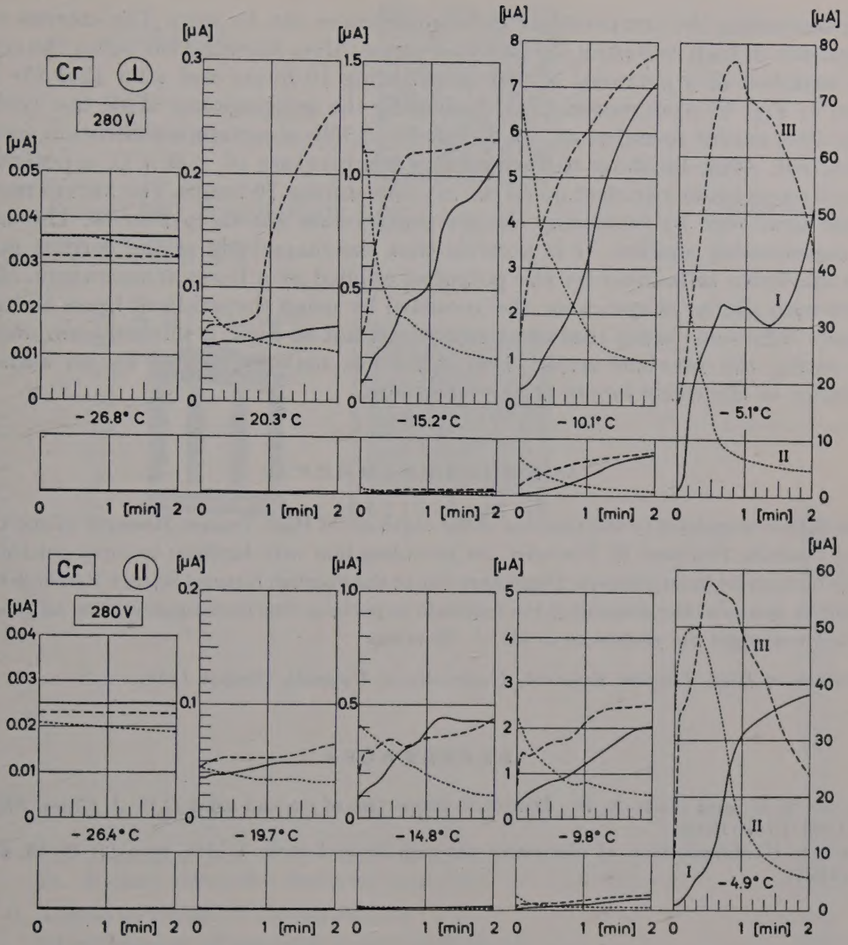

Fig. 16. Current through ice crystals ⊥ and || to the optical axis in dependence on increasing temperature. Chrome-plated electrodes. Rectangular pulses of 2 minutes and 280 volts. Before the measuring series the crystals have been connected with a battery of 280 volts.

the electrodes. By turning the polarity again (curves III) the current increases again, similar to but higher than in case (I).

Fig. 13 shows curves recorded when the crystals were short-circuited the previous night. The (I) curves were recorded with the same polarity as applied before during the previous treatment of the crystals. Therefore curve (I) had not the tendency to increase, the crystals were "cleared" from the carriers and the current decreased. As may be seen in the figure, the dependence on the temperature was considerable. To show the shape of the current variation during the pulses in addition to the curves in a uniform scale, such curves have also been plotted in a suitably enlarged scale. No essential difference is noticeable in the shape of the curves in dependence on the temperature. The curves in Fig. 13 were recorded by decreasing the temperature. In Fig. 14 the curves are shown from recordings of the current on the same day when increasing the temperature. Some differences can be seen. The current was in general not so high as during the previous series. After finishing the series the crystals were switched to a potential of 280 volts during 16 hours and after that the series shown in Fig. 15 were recorded by decreasing the temperature. With the exception of the first curves recorded at −4.3°C and −3.7°C, a certain stabilization seems to be reached. After finishing this series at a temperature of −26.4°C, a potential of 280 volts was again switched on to the crystals during 16 hours. The curves recorded on the next day by increasing the temperature are shown in Fig. 16. The current was considerably smaller. It is possible that the magnitude of the current may be more markedly influenced by the potential applied at a lower temperature. Similar curves with similar shapes were also recorded by using the oxidized brass electrodes, the only difference being that the current was not so high, a phenomenon observed also during the previous series. This difference may be caused by an additional resistance in the oxide layers of the electrodes.

ACKNOWLEDGEMENTS

The author is grateful to the Director of the Institute of High Tension Research of the University of Uppsala, Professor H. Norinder, for providing him with facilities to carry out this work and for his interest in its progress. Thanks are due to the Swedish Natural Science Research Council for placing means at the disposal of the Institute to perform this investigation. The author gratefully acknowledges the assistance of Mr. A. Metnieks.

Institute of High Tension Research, University of Uppsala, August 1956.

REFERENCES

1. AUTY, R. P., and COLE, R. H., Dielectric properties of ice and solid D_2O. *J. Chem. Phys., 20,* 1309–1314 (1952).
2. SIKSNA, R., Conduction of electricity through ice and snow. I. *Ark. fys., 11,* Nr 43, 495–510 (1957).

Tryckt den 13 mars 1957

Uppsala 1957. Almqvist & Wiksells Boktryckeri AB